Origin of the Elements
or
Elements of the Origin

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Near the

Beginning

around

13.7 billion years ago,

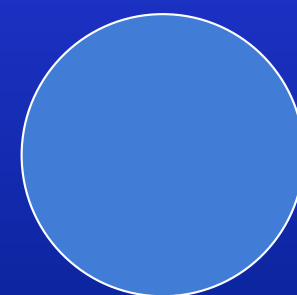
$t=10^{-43}$ seconds,

the ‘Planck time’

$(\sqrt{G\hbar/c^5})$

Quantum Fluctuations
dominated
Space-Time

The Universe might have
been
not much bigger
than
the Planck Length
$r \approx 10^{-32}\ cm$



Lots of Energy
but no matter!

The energy could have been contained in a massless scalar field

and

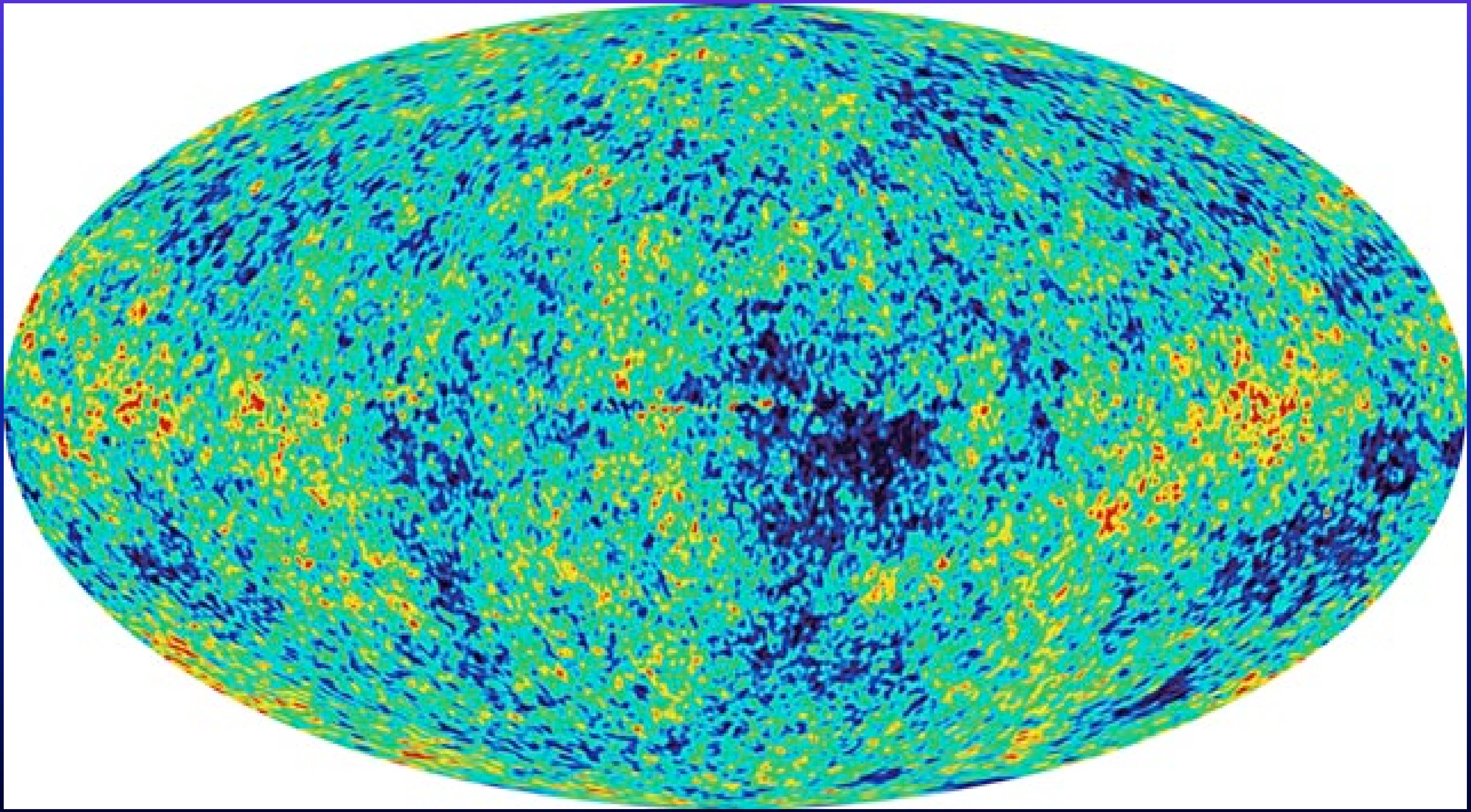
the tension in space-time

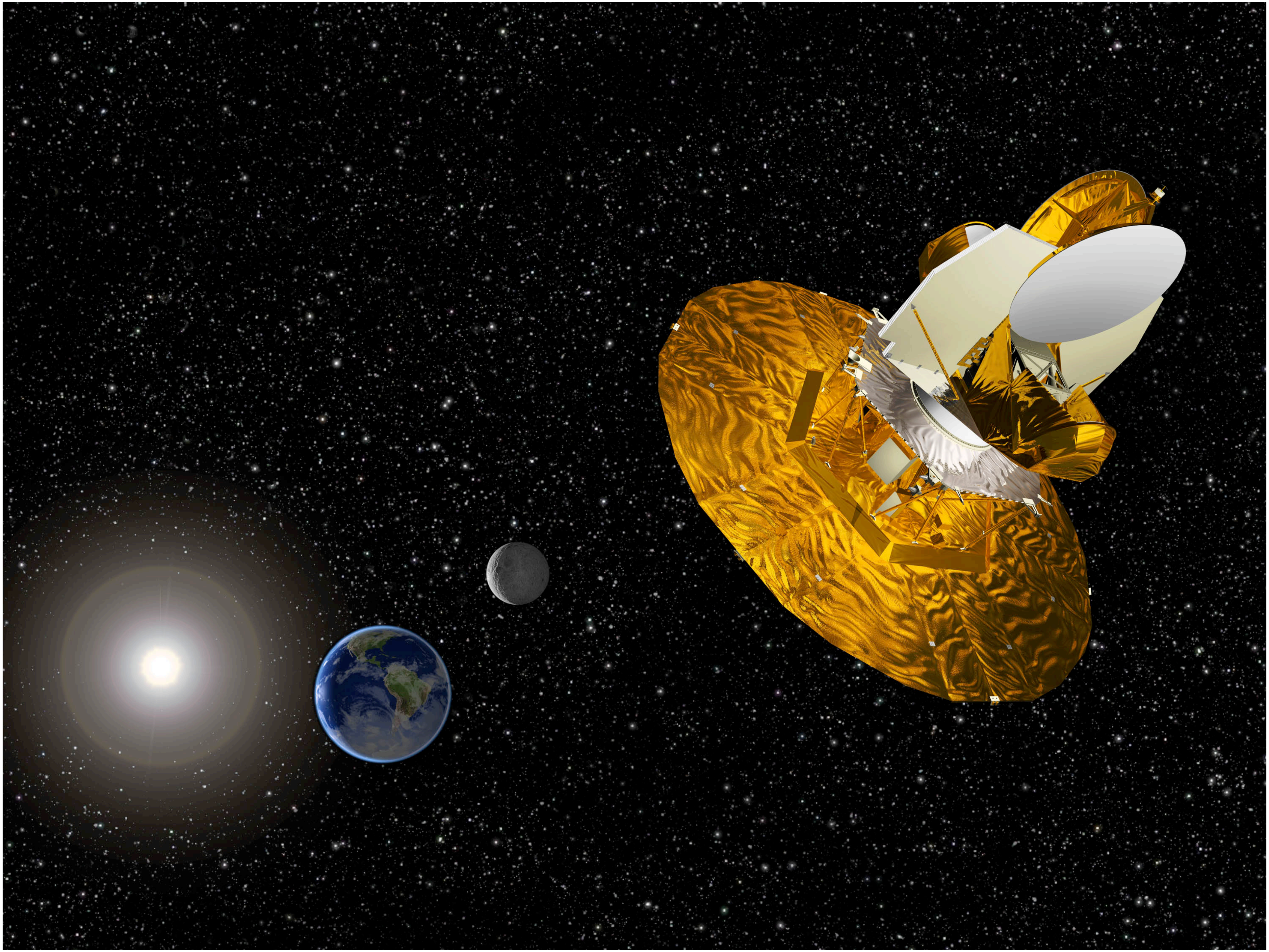
The scalar field
can cause a period
of exponential expansion,
'Inflation',
of the Universe
from 10^{-32} *cm* to 1*cm*!

Inhomogeneities
'washed out'
to 1 part in 10^5
(superstring fluctuations also inflate)

Cosmic Background Explorer
COBE (1992) and
Wilkinson Microwave Anisotropy
Probe (2003)

WMAP of Universe





Scalar field undergoes phase change:

Quantum Condensates

Super-heavy Bosons
Gluons, Photons, Weak Bosons,
Leptons, Quarks,
Baryons, Mesons

Structure Particles: Quarks and Leptons

	Q	M(GeV)
d	-1/3	0.006
u	2/3	0.006
s	-1/3	0.200
c	2/3	1.5
b	-1/3	5.1
t	2/3	178.

	Q	M(MeV)
ν_e	0	<0.003
e	1	.511
ν_μ	0	<0.19
μ	1	105.66
ν_τ	0	<18.2
τ	1	1777.

Interaction
Generated by ‘Gauge Bosons’

Particle	Symbol	Mass (GeV)
Super-heavy	X	$\sim 10^{15}$
Higgs	H^{+}, H^{0}	117.
Gluons	G	Zero
Weak Bosons	$W^{\pm}, Z^{0}$	80.42, 91.19
Photons	γ	$< 2\times10^{-16}$eV

By the elapse time of

t=10^{-6} seconds,

most baryons and antibaryons annihilated.

1 in a billion left as neutrons and protons

“Radiation Era”

Plasma of γ, ν, $\bar{\nu}$, e^-, e^+, p, n

Temperature about 10^{12}K

Expansion continued more gently

$R \propto t^{1/2}$, $T \propto t^{-1/2}$

At $T \approx 10^{11}$K, (10^{-2} sec) neutrinos decouple from matter

Below $T \approx 3 \times 10^{10}$K deuterons stick together to make Helium-4

At $T \approx 10^9$K (190 seconds), positrons annihilate with electrons to make photons

$$e^+ + e^- \rightarrow \gamma$$

Neutrons taken into Helium or decayed.

Left: γ, ν, $\overline{\nu}$, e^-, p, He^{++}(23% wt)

(He abundance sensitive to neutron lifetime, $\tau_{1/2}$=10.23 minutes, and number of species of neutrinos, N=3 from Z^0 decay!)

Beginning of ‘Matter Era’

t = 380,000 years,

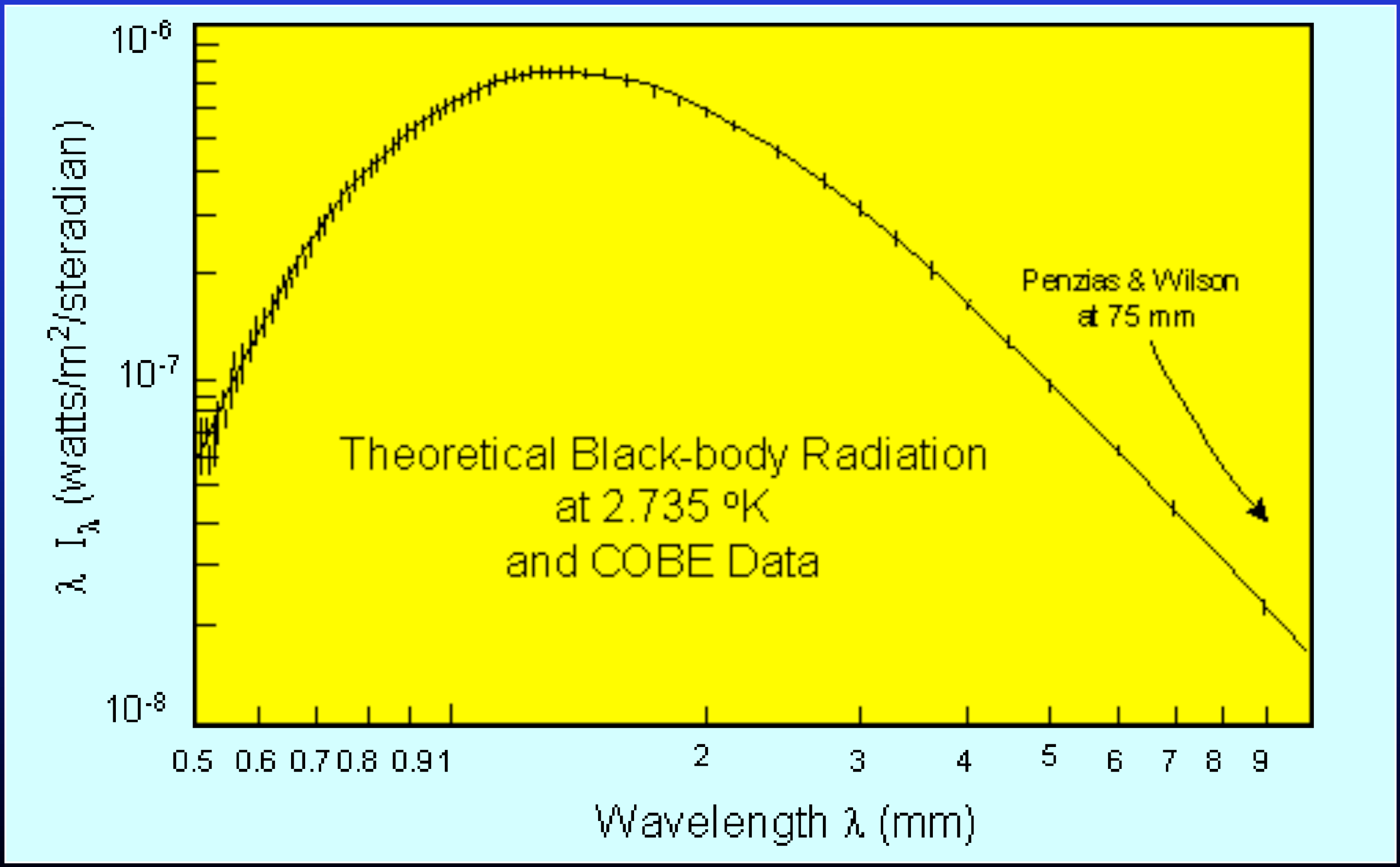
$T \approx$ 5000 K

Matter ‘decoupled’ from radiation when neutral atoms formed.

(Visible Matter 4%, Dark Matter 23%, Dark Energy 73%)

Background radiation predicted by Gamow and Alpher (1948, GWU)

Residual Background found by Penzias and Wilson in 1965 COBE 2000 data:



‘Stability Gaps’ at A=5 and 8 stopped primordial nucleosynthesis

											^{12}N -1.96	^{13}N -2.00	^{14}N 99.63	^{15}N 0.37
							^{8}C -20.7	^{9}C -0.90	^{10}C 1.29	^{11}C 3.09	**^{12}C 98.9**	**^{13}C 1.1**	^{14}C 11.26	^{15}C 0.389
						^{7}B -21.4	^{8}B -0.113	^{9}B -18.1	**^{10}B 19.9**	**^{11}B 80.1**	^{12}B 3.08	^{13}B 3.02	^{14}B 2.92	^{15}B 2.73
					^{6}Be -20.3	**^{7}Be** 6.66	**^{8}Be** -16.1	**^{9}Be 100**	**^{10}Be** 13.7	**^{11}Be** 1.14	**^{12}Be** -1.26		**^{14}Be** -2.40	
				^{5}Li -21.5	**^{6}Li 7.5**	**^{7}Li 92.5**	**^{8}Li** -0.076	**^{9}Li** -0.752		**^{11}Li** -2.09				
		^{3}He .000138	**^{4}He 99.9**	**^{5}He** -21.1	**^{6}He** -0.093	**^{7}He** -20.5	**^{8}He** -0.924							
^{1}H 99.985	**^{2}H 0.015**	**^{3}H** 8.59												
^{1}n 2.8				⇑			⇑							

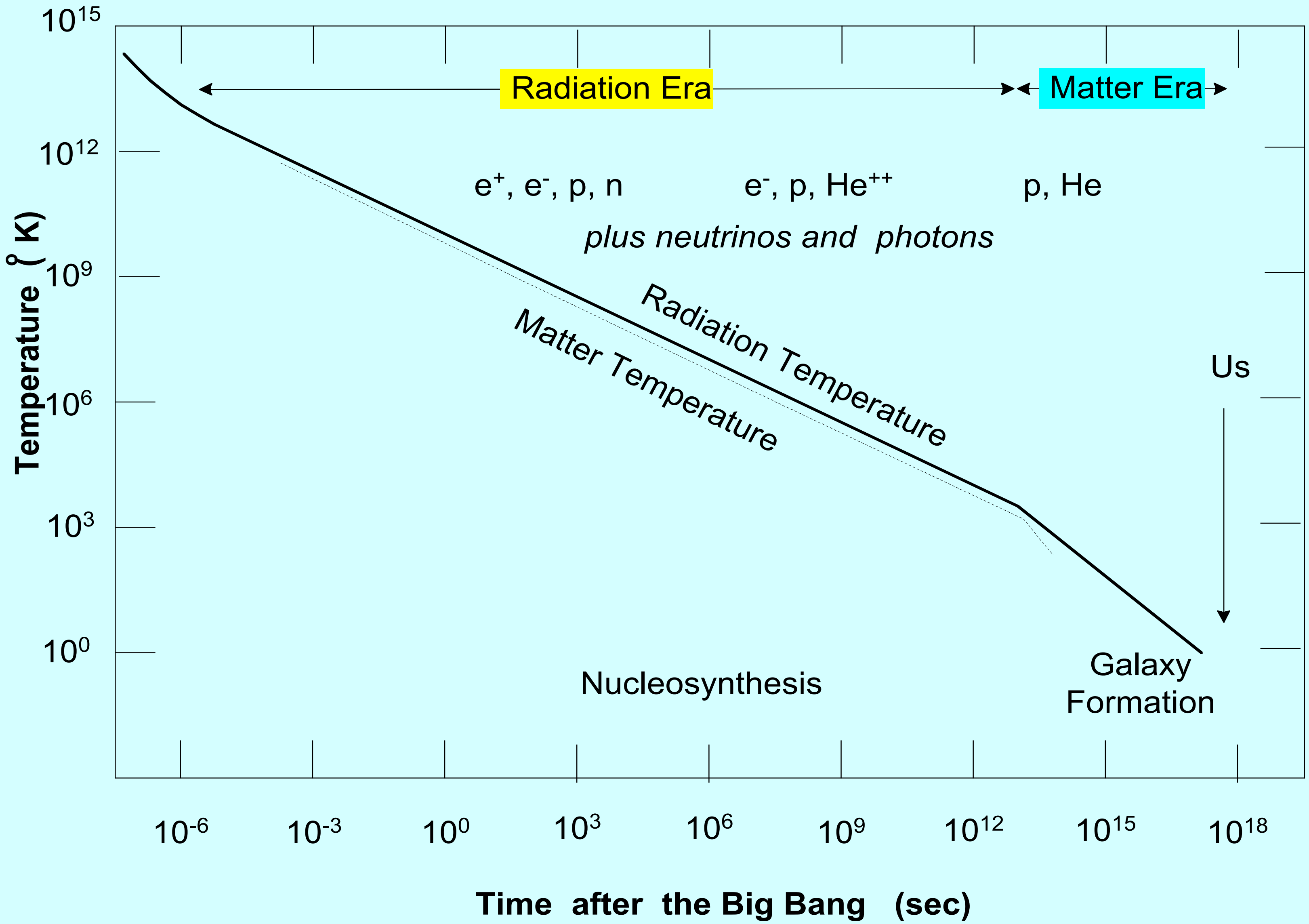
Stable Element Relative Abundance	Unstable Element LOG (Lifetime [sec])

Primordial Abundances of Light Elements

Element	*Mass Fraction, observed*	*Mass Fraction, theory*
^{1}H	0.75	0.76
^{2}He	$(2.5 \pm 1.5)\times10^{-5}$	2.46×10^{-5}
^{3}He	$(4.2 \pm 2.8)\times10^{-5}$	4.2×10^{-5}
^{4}He	0.23 ± 0.02	0.23
^{6}Li	$(320 \pm 200)\times10^{-12}$	160×10^{-12}
^{7}Li	$(4800 \pm 3000)\times10^{-12}$	270×10^{-12}

Data from spectroscopy of Population II (old) stars and gas

Time and Temperature



t = 200 million years

Galaxies and Stars form

Rate of heavier element production
strongly dependent
on nuclear stabilities, resonances,
temperature, and Coulomb barrier

Essence of Stellar Dynamics

Baryon, Lepton, Charge, & Energy Conservation

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\varepsilon(\rho, T)$$

Local Mechanical Equilibrium

$$\frac{dp(r)}{dr} = -\rho(r)\frac{G}{r^2}\int_0^r \rho(r')4\pi r'^2 dr'$$

Local Thermal Steady-State

Equation of State

$$p(r) = \frac{k}{\mu}\rho(r)T(r) + \frac{4\sigma}{3c}T(r)^4$$

Radiation flow

$$\frac{dT(r)}{dr} = -\frac{3\kappa\rho}{4\sigma T^3}\frac{L(r)}{4\pi r^2}$$

Convective flow

$$\frac{dT(r)}{dr} = \left(1 - \frac{c_v}{c_p}\right)\frac{T(r)}{p(r)}\frac{dp(r)}{dr}$$

Element Production in Stars

Reaction rate per unit number density:

$$\langle \sigma \, v \rangle = \sqrt{\frac{8}{\pi \mu (kT)^3}} \int_0^\infty \sigma(E) E \, e^{-\frac{E}{kT}} \, dE$$

Maximum rate:

$$E_0 = \left(\frac{\sqrt{2\mu} \, \pi \, e^2 Z_1 Z_2 \, kT}{\hbar} \right)^{2/3}$$

Jumping the A=5 & 8 Barrier

Beryllium-8 resonance predicted by Fred Hoyle from Carbon production via $^{8}Be(\alpha,\gamma)^{12}C$

Resonance was later found.

Too short lived to help in early universe production.

Oxygen production: Subthreshold resonance in

$^{12}C(\alpha,\gamma)^{16}O$

Time Scales for Element Production in Stars

Hydrogen burning: 1 million to 20 million years

Helium burning: 100 thousand to 100 million years

Carbon burning: 500 to 1000 years

Neon burning: 1 year

Silicon burning: 1 day

Iron made from excess neutrons

in reactions such as $^{22}Ne(\alpha,n)^{25}Mg$

Supernovae Element Production

Flux of excess neutrons, e.g.

$$^{12}C(p,\gamma)^{13}N(e^{+})^{13}C(\alpha,n)^{16}O$$

and neutrinos

$$p + e \rightarrow n + \nu$$

convert lighter elements to heavier ones in a matter of seconds to days

Abundances of the Elements